

Experience With An imaging Infrared Radiometer In A Simulated Space Environment

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ABSTRACT

A commercially available imaging infrared radiometer, an Inframetrics 760 system, was subjected to simulated space and Martian environments in JPL's 2.5 ft and 10 ft space simulators for a total of 108 hours. Initially, the IR camera was integrated with the Satellite Test Assistant Robot (STAR) system which demonstrated successful operation in late 1994. During this initial demonstration, the IR camera experienced 24 hours of a hard vacuum with simulated space temperatures between -190°C to $+25^{\circ}\text{C}$. Subsequently, the IR camera was subjected to 12 hours of a simulated space and 72 hours of a simulated Martian environment during the Mars Rover test. Equipped only with thermostatically controlled heaters to prevent undercooling, the IR camera operated continuously during these periods and provided numerous images of the simulator interior, a reference target, and the Mars Rover. The reference target consisted of nine samples of different materials used in typical aerospace thermal designs. The emittance range covered 0.02 to 0.90. The target temperature range was varied from -80°C to $+55^{\circ}\text{C}$. The IR camera was reliable and provided quality images throughout this range but measurement accuracy was a strong function of target temperature and emittance. Best results for high emittance targets were within 12°C at -80°C to within 1°C at $+55^{\circ}\text{C}$.

1. INTRODUCTION

In a continuous effort to improve JPL's space Simulation facilities and data acquisition methods, the STAR system was conceived to provide non-contact temperature measurements of flight hardware inside a space simulator. Under typical operating conditions a simulated space environment includes a hard vacuum of at least 1×10^{-5} torr and background temperatures as low as -190°C . The STAR system was designed to operate in this environment and to provide remotely controlled actuation. In its current configuration the STAR system is capable of controlling the elevation, and the pan and tilt angle of a platform to which an IR camera is mounted. Control is exerted through a joystick or a software driven user interface. Part of this interface is the simulated control panel of the IR camera. Feedback is provided through the graphical user interface and by a visual image of two CCD cameras that are aligned with the IR camera. Throughout the STAR demonstration all pertinent data were recorded continuously for post test evaluation. These data included temperature measurements by thermocouples, a data log of all actuations performed, and video tapes of all IR images. The STAR system performed well and the demonstration was an unqualified success. A detailed report on the STAR system performance is provided in Reference 1.

This paper focuses on the setup and performance of the IR camera system in simulated space environments. In a very short time, as is typical for IR imaging systems, the 25 ft simulator interior was scanned and several examples of previously unknown temperature discontinuities were discovered. Additionally, a reference temperature target was imaged at different temperature levels and during temperature transitions to provide data for performance characterization. During a subsequent opportunity, the IR camera was tested for another 84 hours in simulated space and Martian environments.

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2. ENVIRONMENTAL SIMULATION AND THE STAR SYSTEM

JPL maintains space simulation chambers of various sizes and capacities to accommodate test needs for many different space missions. Two opportunities to gain experience with an IR camera under simulated space conditions arose during the STAR performance test and during the Mars Rover test. During these simulations, the IR camera was exposed to vacuum, deep space temperatures, and a simulated Martian atmosphere.

2.1 Facilities and environments

JPL's largest space simulator is of cylindrical shape with a 25 ft diameter and a height of 85 ft. It is capable of solar simulation by reflecting a radiant beam, produced by an array of 37 xenon arc lamps, off a reflecting mirror mounted at the top of the chamber. A picture of the simulator is given in Figure 1 below. The walls and floor of the simulator are lined with finned aluminum shrouds, painted black. The wall and floor temperature can be controlled between -190°C (liquid nitrogen) and -150°C . The highly reflective mirror at the top completes the thermal enclosure. The entire volume can be evacuated to pressures in the 5×10^{-6} torr range.

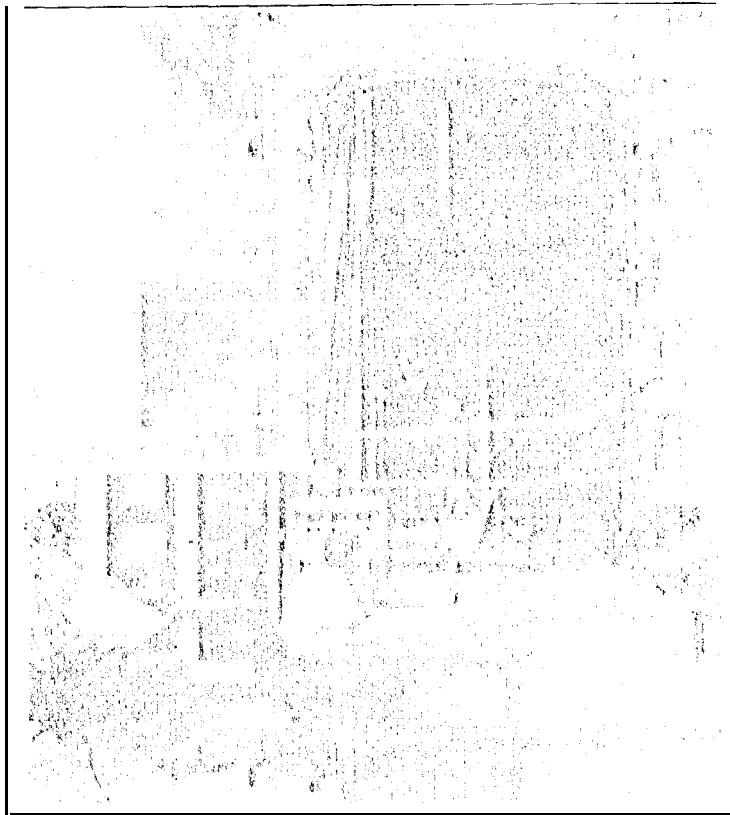


Figure 1: JPL's 25 ft simulator, STAR controls in foreground

Subsequent to its refurbishment, the 25 ft space simulator was undergoing a series of tests to characterize its performance. The STAR demonstration was integrated into one of these tests. During the STAR test, a high vacuum was maintained and the environmental temperatures were varied from -190°C to 25°C . Solar simulation was not exercised during the STAR demonstration.

The Mars Rover test was conducted in JPL's 10 ft vertical chamber. The useful height is about 20 ft and the diameter is 10 ft. Vacuum and temperature simulation capability is very similar to the 25 ft chamber described above. This chamber, however, does not have solar simulation capability.

During the first part of the Mars Rover test, simulating the cruise of the spacecraft from Earth to Mars, space conditions were simulated with a vacuum environment and temperatures of approximately -35°C . The second part of the test simulated Martian surface conditions with temperatures in the range from -80°C to -20°C in a nitrogen atmosphere at 8 torr.

2.2 STAR

STAR, the Satellite Test Assistant Robot, is an innovative tele-robotic inspection system. It is capable of viewing a space flight article in the test chamber from different vantage points by using a set of two vacuum rated high resolution CCD video

cameras and an IR camera. A three axis instrument platform, consisting of a 25 ft high vertical axis and a pan/tilt unit riding on a carriage assembly driven by a cleanroom quality stainless steel belt drive, can be remotely controlled by an operator. A graphical user interface, shown in Figure 2, is provided by a computerized control station. Infrared camera settings, image manipulation and capture, lighting adjustment, and elevation and orientation control can be remotely exercised. User interaction is supported by touchscreen or mouse. A detailed description of the STAR thermal vacuum test can be found in Reference 2.

3. IMAGING RADIOMETER

The imaging radiometer, an Inframetrics 760 system, is an "off the shelf" product. A preliminary test conducted in September 1993 by JPL on an identical imaging system confirmed that this camera is capable of extended and continuous operation in vacuum. The prominent feature that enables its operation in a vacuum environment is a miniaturized Stirling cooler that is built into the camera and is used to provide cooling of the JlgCdTe detector that is sensitive in the 3-12 micrometer region. The IR camera was equipped with the standard 1 x lens. No other external optics were used.

3.1 Design modifications

In order to provide temperature control of the radiometer, it was instrumented with thermostatically controlled foil heater elements that were placed on the scanner housing together with thermocouples for temperature sensing. Figure 3 shows the scanner together with one equally instrumented CCD camera on each side.

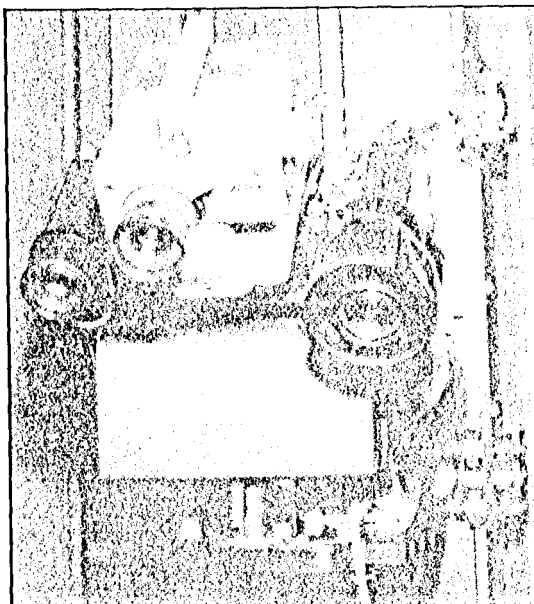


Figure 3: Scanner instrumented with heaters

The scanner and CCD cameras were then blanketed with multi-layer insulation (MLI) to provide protection from solar insolation, to improve temperature uniformity, and to reduce heater power consumption. The final assembly is shown in Figure 4. These were the only modifications made to the IR camera.

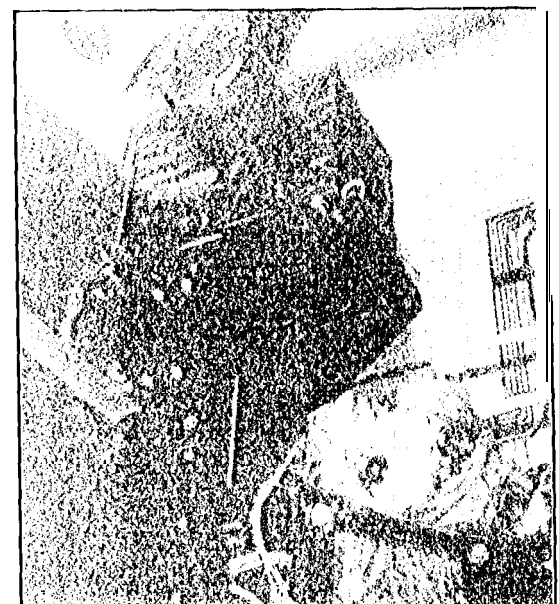


Figure 4: Scanner after MLI installation

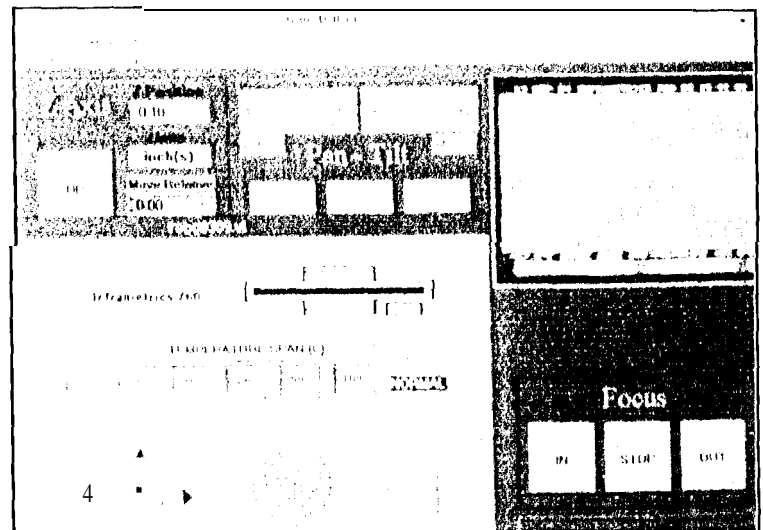


Figure 2: STAR touchscreen control panel

3.2 Scanner cable

During the STAR test, the scanner control was located outside and below the simulator, in the basement directly underneath the scanner. To accommodate the separation between the scanner and the control unit, a new cable was built with connectors compatible with chamber feed-throughs. The new cable had a length of approximately 40 ft. This is considerably longer than the standard cable available with the IR camera. The longer cable is thought to be responsible for some irregularities observed late during the STAR test. These irregularities are described in more detail in the Results section of this paper.

4. REFERENCE TARGET

A reference target was placed inside the vacuum chamber to support an independent assessment of the imaging radiometer's performance. The target consisted of a temperature controlled copper plate heat exchanger. The temperature of this heat exchanger could be controlled over a wide range. The copper plate heat exchanger design provided temperature control for all samples with a uniformity to within 2°C throughout the STAR test. Each target temperature was measured continuously by two thermocouples that were mounted right behind each sample surface on the copper plate. All measurements were recorded for later data analysis. A picture of the target is shown below in Figure 5.

4.1 Target materials

The copper plate surface was painted black and held nine samples of different spacecraft materials. The sample materials were selected to provide typical spacecraft surface properties and included gold, silver, aluminized Kapton, aluminized Mylar, white paint, black paint, and solar cells. The target material's emissivities were measured at room temperature prior to the test with a Gier Dunkel Reflectometer. These values, summarized in Table 1 below, were used for subsequent temperature measurements.

Table 1: Target Material Emissivities at Room Temperature		
1	flat white	0.90
2	glossy white	0.88
3	gold	0.02
4	black Kapton	0.80
5	embossed aluminized Kapton, aluminum side	0.12
6	solar cell	0.82
7	aluminized Kapton, Kapton side	0.52
8	aluminized Mylar, aluminum side	0.03
9	beta cloth, white	0.90
10	background on copper plate, CAT-A-LAC Black	0.85

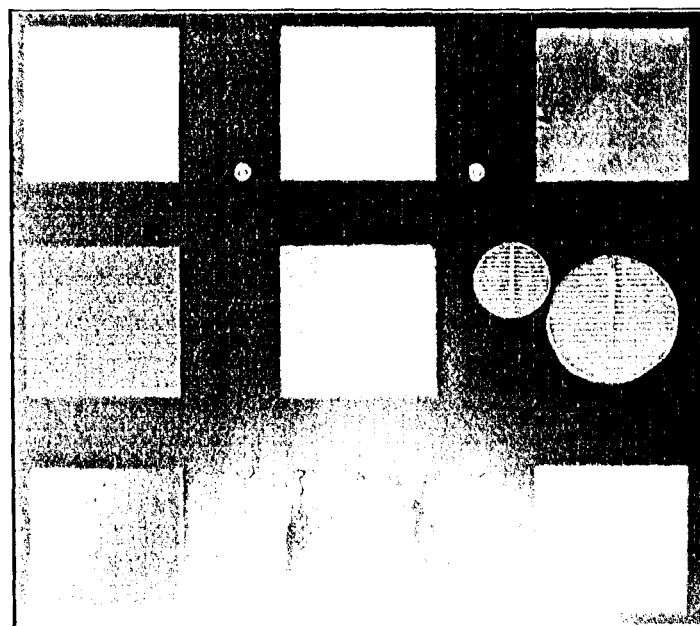


Figure 5: Reference target

Sample material correspondence in Figure 5 to the numbering in Table 1 is left to right and starting at the top row, e.g., the upper left corner is sample #1, the center sample is #5 and the lower right corner sample is #9.

5. OBSERVATIONS AND RESULTS

The STAR test resulted in 18 hours of images recorded on video tape and 24 images saved on a floppy disk. In addition, a significant portion of the Mars Rover test was videotaped and several images were saved on floppy disk.

5.1 STAR Test data comparison

For this comparison, ambient, hot, and cold reference target temperatures have been selected to give a representative sample of IR camera performance. Consistent with typical IR camera experience, the accuracy of measured sample temperatures depends strongly on the emittance of the sample surface and the target temperature. Results are presented in Table 2, summarized and grouped by emittance range and target temperature.

Table 2: Summary of typical temperature measurement accuracy, $\Delta T_{(IR \text{ image} - \text{thermocouple temperature})} - ^\circ C$						
target temperature	high emittance $\epsilon = 0.8 - 0.9$		medium emittance $\epsilon = 0.52$		low emittance $\epsilon = 0.02 - 0.12$	
	direct measurement	after emittance correction ¹⁾	direct measurement	after emittance correction ¹⁾	direct measurement	after emittance correction ¹⁾
-85/-75	-125	-112	+21	no data	+52	no data
-75/-6s	+21	+7	+18	no data	+87	no data
23	-0.6	-1.1	-0.2	-2.9	-11.5	-16.4
40	-10.3	-0.8	+2.3	-2.4	-5.0	-19.9
55	-0.5	-1.7	+3.7	-2.1	-16.3	-29.3

- 1) The emittance correction referred to in the table consists of imaging a target at two known and uniform temperature levels. A software program then calculates local emittances and background temperatures and applies this information to subsequent images on a pixel by pixel basis.

It is remarkable that for emittances of 0.5 and higher even extreme cold targets were detected. The accuracy deteriorates sharply from ambient measurements but any relative measurements, such as temperature distributions, can still be performed. The low temperature limit of $-85^\circ C$ is the lowest target temperature encountered. The lowest temperature that can be sensed with the IR camera was not determined but appears to be well below the $-20^\circ C$ specified by the manufacturer.

The unsatisfactory accuracy of the low emittance group is partially due to the inherent difficulty of measuring emitted energy from a surface that primarily reflects energy. In this sample group, two of the three surface had reflectances of 97% and 98%. It is possible to achieve better results but this test was not conducted to determine maximum performance limits on the imaging system. The primary goal was to establish the feasibility of operating an IR camera under simulated space conditions.

5.2 Image quality

No noticeable degradation in image quality has been observed. Every image that has been analyzed is of the same quality in terms of clarity, contrast and accuracy as images taken under regular ambient conditions. A sample of the test images is given in Figure 6 and Figure 7 on the next page.

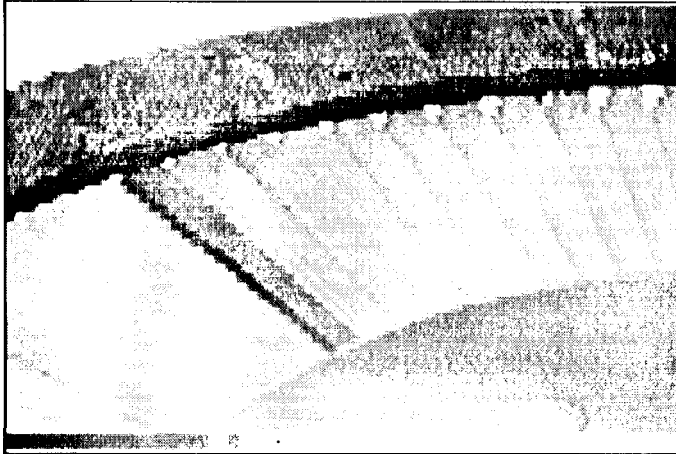


Figure 6: Discontinuity in cooling fin temperatures

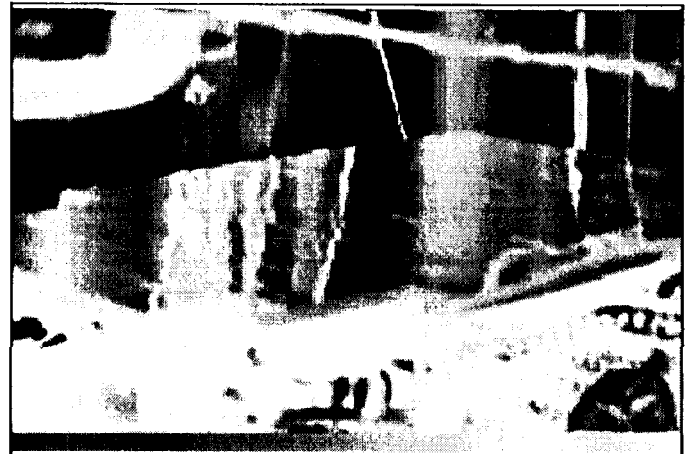


Figure 7: Mars Rover

5.3 Maintenance and diagnostics

The IR camera provided several useful images of the temperature distribution of the chamber enclosure during real time operation, information that usually is not available because of the sheer size of the simulator. Previously unknown temperature discontinuities were discovered, indicating non-uniform cooling on one shroud fin, as can be seen in the image in Figure 6 above. In the future, mapping of the test chamber prior to a test can be routinely and quickly performed. It is also possible to quickly and easily map the uniformity of the solar simulator employing a technique as described in Reference 3.

5.4 Contamination

The IR camera can potentially represent a contamination source to other test articles because its construction did not require the use of low outgassing and vacuum compatible materials. For the test described in this paper no special steps to clean the camera, such as a bake-out, were taken. The test chambers are equipped with liquid nitrogen flooded cold plates designed to collect any contaminants. No adverse effects on test operations have been observed which are due to the presence of the IR camera,

Another concern was contamination of the camera optics by other contamination sources present in the test chamber. Based only on visual inspection and the quality of the images taken, a judgement can be made that this has not been a problem. This is further supported by the fact that the IR camera is temperature controlled. Since scanner temperatures are maintained near ambient, it is less likely that contaminants will condense on the camera optics rather than the cold plate which is maintained at much lower temperatures. If additional external optics are used, the increased distance of these optics from the temperature controlled scanner body will lead to lower temperatures. The issue of contaminating IR camera optics may have to be re-evaluated in this case.

5.5 Scanner cable

The scanner cable, connecting the scanner inside the test chamber to the externally located control unit, had to be considerably lengthened from the factory provided 4 ft cable to a 40 ft JPL custom made cable. In addition to this modification, signals had to pass through feedthrough connectors at the chamber's bulk head. During the STAR test the IR camera operation experienced difficulties when an attempt was made to change the scanner filter setting. These difficulties occurred when the filter wheel control did not respond and the camera controller did not receive confirmation that the newly selected filter setting had been established. As a result, the entire control software "hung up" and the system had to be rebooted. The described scenario was repeatable and a clear relationship between a "hung" controller and the attempt to change filter settings was established.

The above observations are consistent with previous experiences using a 25ft cable under ambient conditions. The filter wheel problem occurred in the same manner then. The remedy for the tests described in this paper was to not change the filter wheel setting. For future application it may be considered to put the desired filter in the default position since it is unlikely that the performance can be improved when using a long cable.

6. CONCLUSIONS

Prior to the use of an infrared imaging system inside a space simulator, the only way to obtain non-contact temperature measurements was to view the test article through an IR transparent window. This led inevitably to viewing constraints caused by the limited size of the window (small because of high cost) and the low probability that the window location was compatible with the overall test configuration. By providing an IR imaging capability inside the test chamber, especially in conjunction with the maneuverability provided by the STAR system, several obvious advantages are realizable:

Every external surface, stationary or moving, can be scanned and the amount of traditional instrumentation, e.g., thermocouples, can be reduced. The new capability also provides a recovery mechanism from failed sensors without the need to interrupt the test.

Unexpected thermal behavior of the test article can now be observed and recorded in real time, when inadequate instrumentation has been provided.

The IR camera provides an image of the temperature distribution of the entire viewing area rather than spot measurements which don't provide the same intuitive overall picture as does an IR image.

It needs to be pointed out that IR imaging is no substitute for internal temperature sensors and that external surfaces may not always be suitable for IR imaging. Very low temperatures and possibly high reflectances can make a temperature measurement by IR imaging unreliable or impossible. But the demonstrated ability to use an IR imaging system under simulated space conditions is an exciting new capability that will be routinely used at JPL to supplement existing test instrumentation. Once long term reliability has been proven, it is even perceivable that an IR camera system such as the one tested can be used directly in space flight applications as a low cost alternative to current IR imaging systems. Usage on STS appears possible.

7. ACKNOWLEDGMENTS

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8. _____

1. D. McAfee, M. Long, K. R. Johnson, G. Siebes, "Performance of the Space Satellite Test Assistant Robot (STAR) in JPL's Space Simulation Facility", 29th Aerospace Mechanism Symposium, Johnson Space Center, May 1995.
2. D. McAfee, M. Long, "Satellite Test Assistant Robot (STAR) Thermal Vacuum Test Report," JPL Document D-12384 (internal), December 1994.
3. Glazer, S., Siebes, G., "Infrared Radiometric Technique for Rapid Evaluation of Heat Flux Distribution Over Large Areas," Proceedings SPIE: Thermosense XI Conference, Orlando, FL., March 1989.